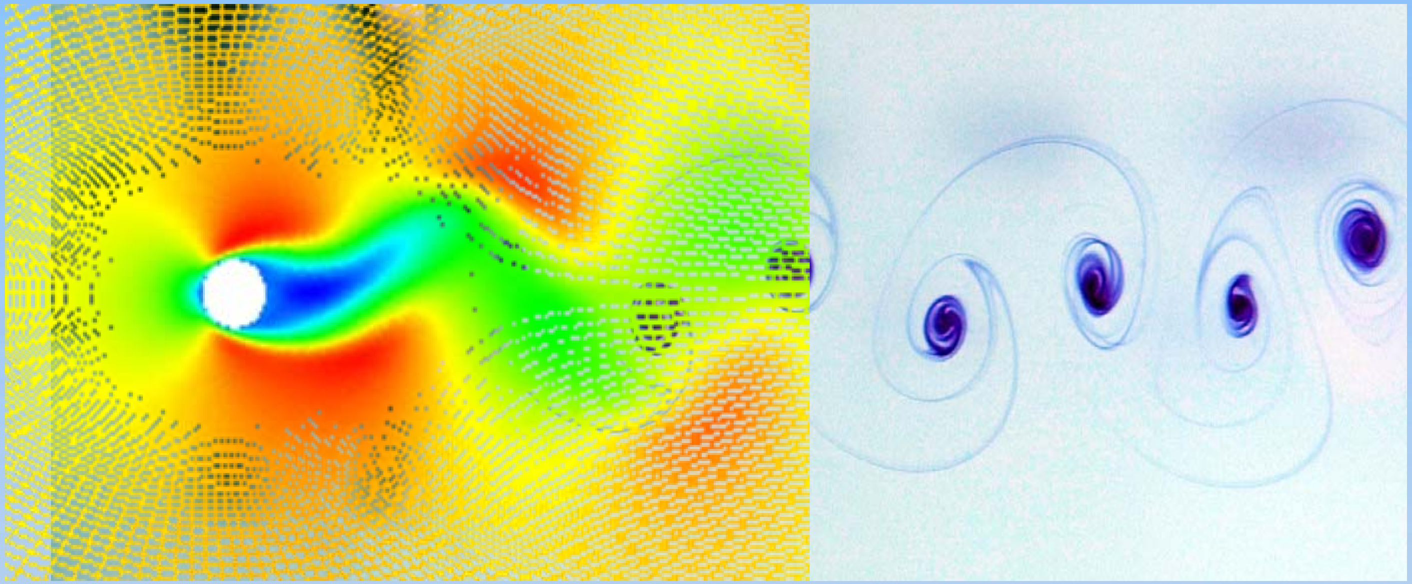
Feedback Control of a Circular Cylinder Wake



Integrating CFD and Experiments in Aerodynamics
20-21 June, 2007

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What is Feedback Flow Control?

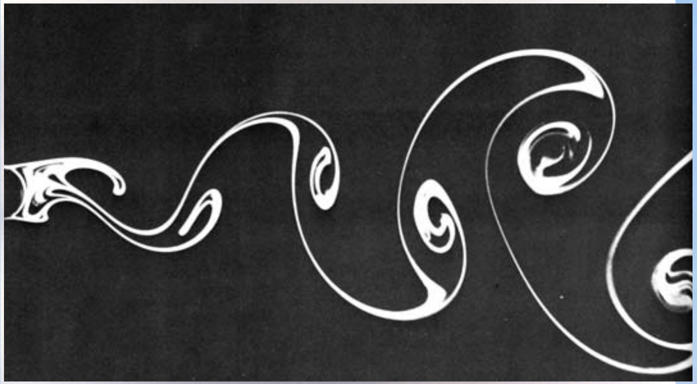
- Flow Control
  - Influence the flow field to achieve a desired effect using *minimal* actuation power
    - Passive
      - Vortex generators
    - Active
      - Synthetic jets
      - Time-dependent (periodic) blowing and suction
      - Piezo-electric micro components
- Feedback
  - Sensors in the wake measure instantaneous flow quantities (velocity, pressure) at given points
  - Actuation based on sensor information

Why Feedback Flow Control?

- Bluff bodies (e.g. on UAVs) serve vital *operational functions*, but they are *aerodynamically detrimental*
- *Flow separation* results in a wake behind the bluff body
  - characterized by unsteady *vortex shedding*
    - results in drag, noise, and vibration
    - is detrimental for operation, structural integrity
- “Passive” designs are impractical or inhibit functionality
- “Active” methods are point designs
- ***Feedback flow control*** is an effective way of suppressing self-excited flow oscillations without modifying the geometry

Predator UAV

http://www.defense-update.com/products/p/predatorB.htm



http://www.airforce-technology.com/projects/hunter

How to Feedback Flow Control?

Modeling wake dynamics for controller design

Model Independent Approach

- Simple to implement experimentally
- Little success in past 30 years

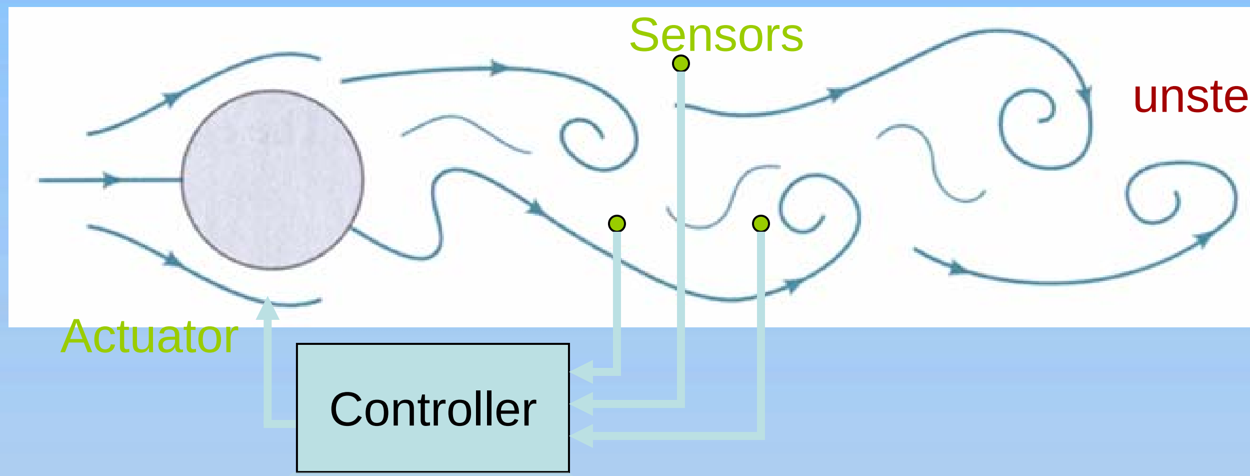
Direct Navier Stokes Approach

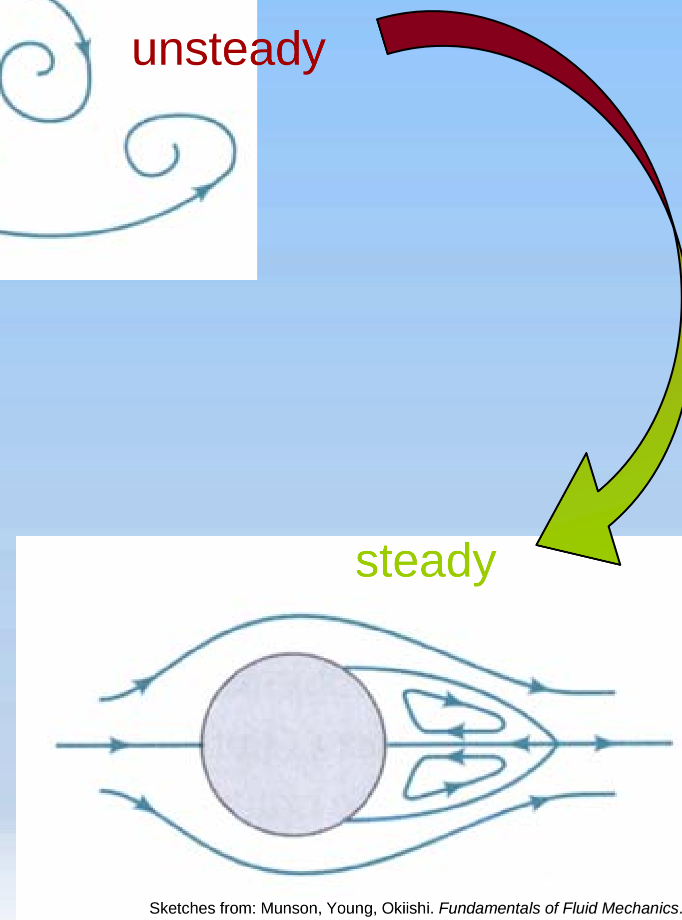
- Ideal control approach, complete set of equations
- Computationally very intensive
- Cannot be implemented in real time in the near future

Low-Dimensional Approach

- Recent developments in effective low-dimensional models
- Can be implemented with relative ease
- Model building is tough

Cylinder Wake Feedback Control





Sketches from: Munson, Young, Okiishi. *Fundamentals of Fluid Mechanics*. p 601.

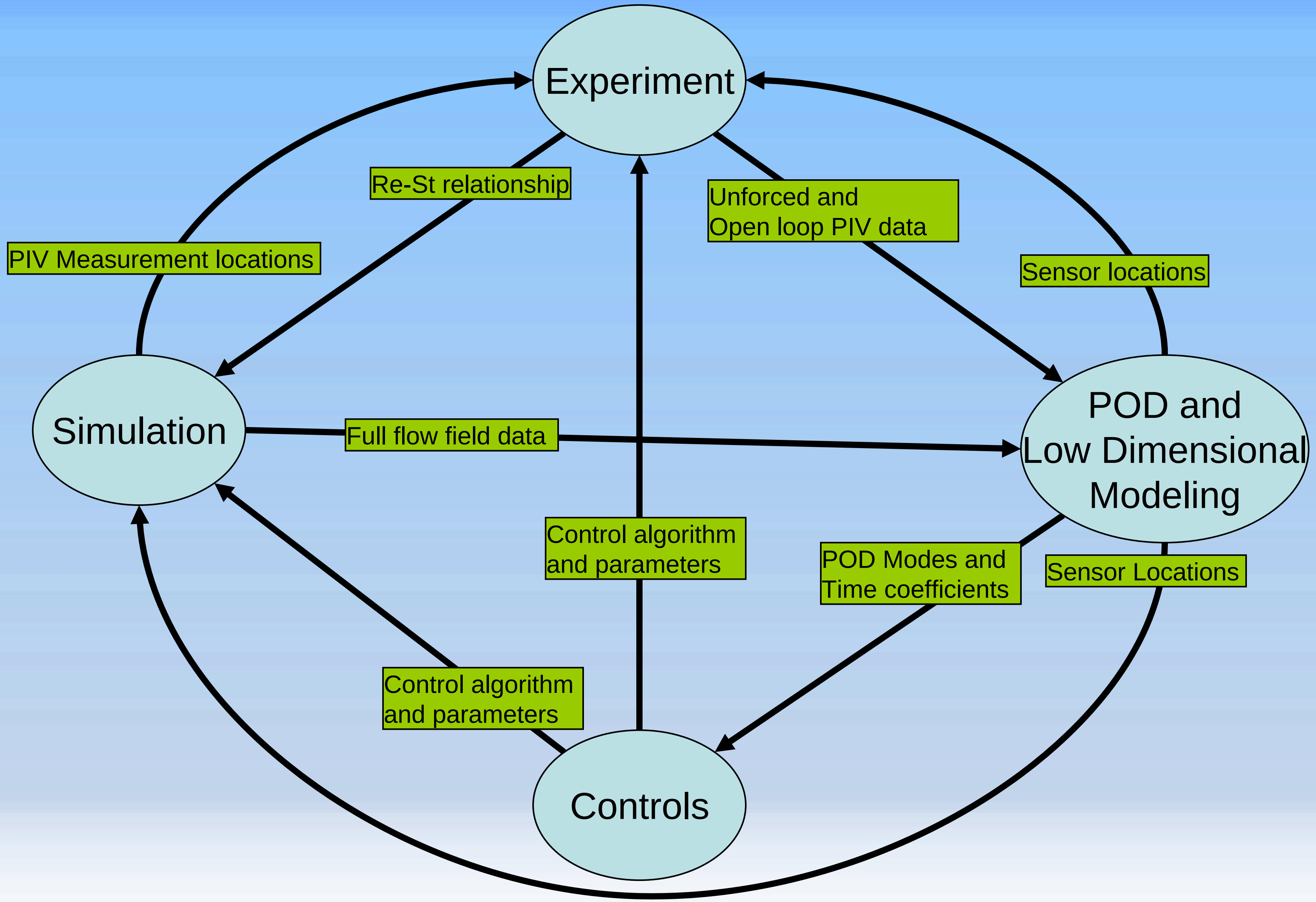
Goal: Develop a feedback control strategy to suppress the vortex street of a cylinder at Reynolds numbers of 100

Low Pass Filter $F_c = 4*F_n$

PD Controller (acts on POD Mode 1)

Mode Estimator (Least Square)

Collaborative Research



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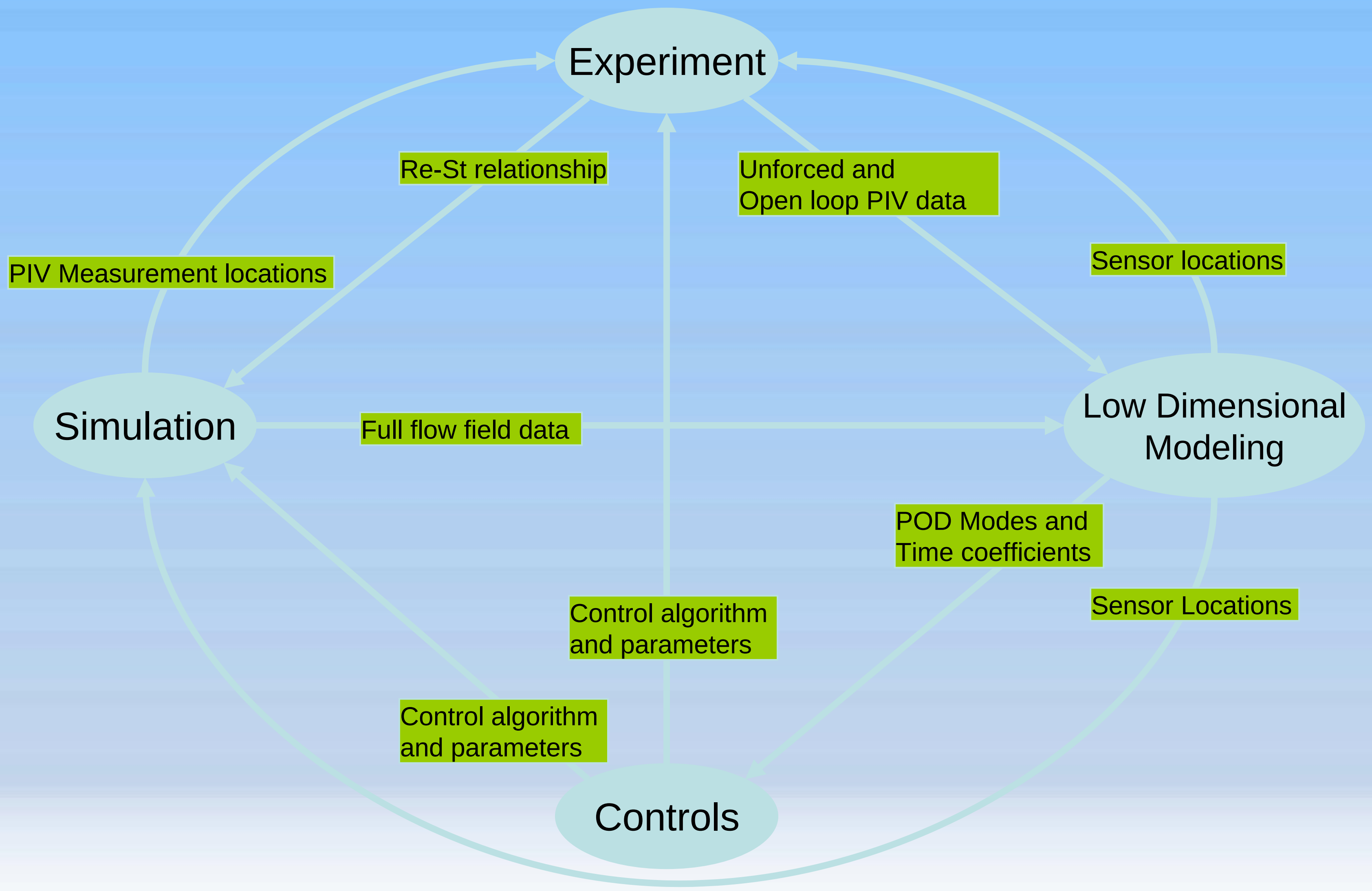
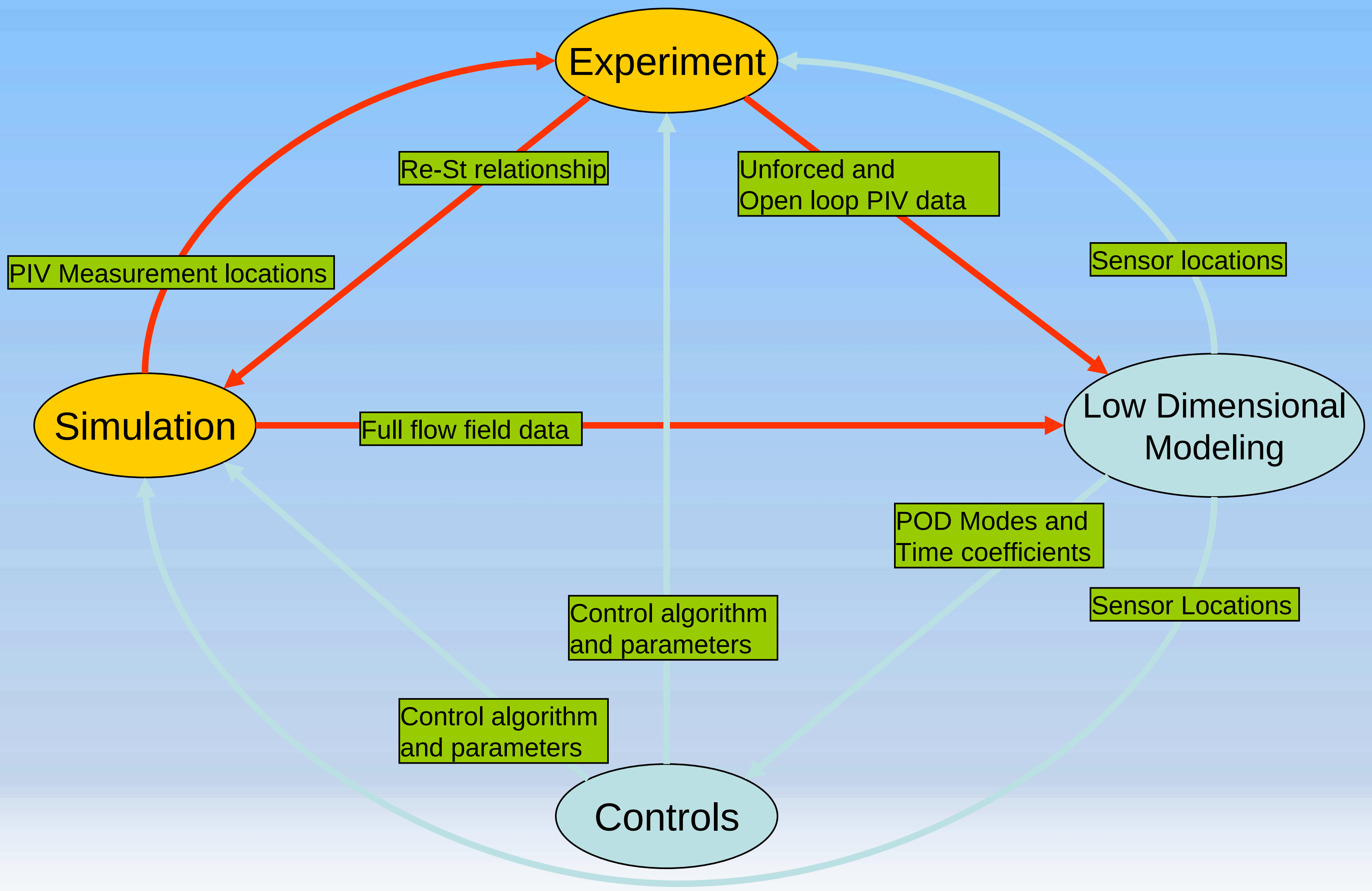
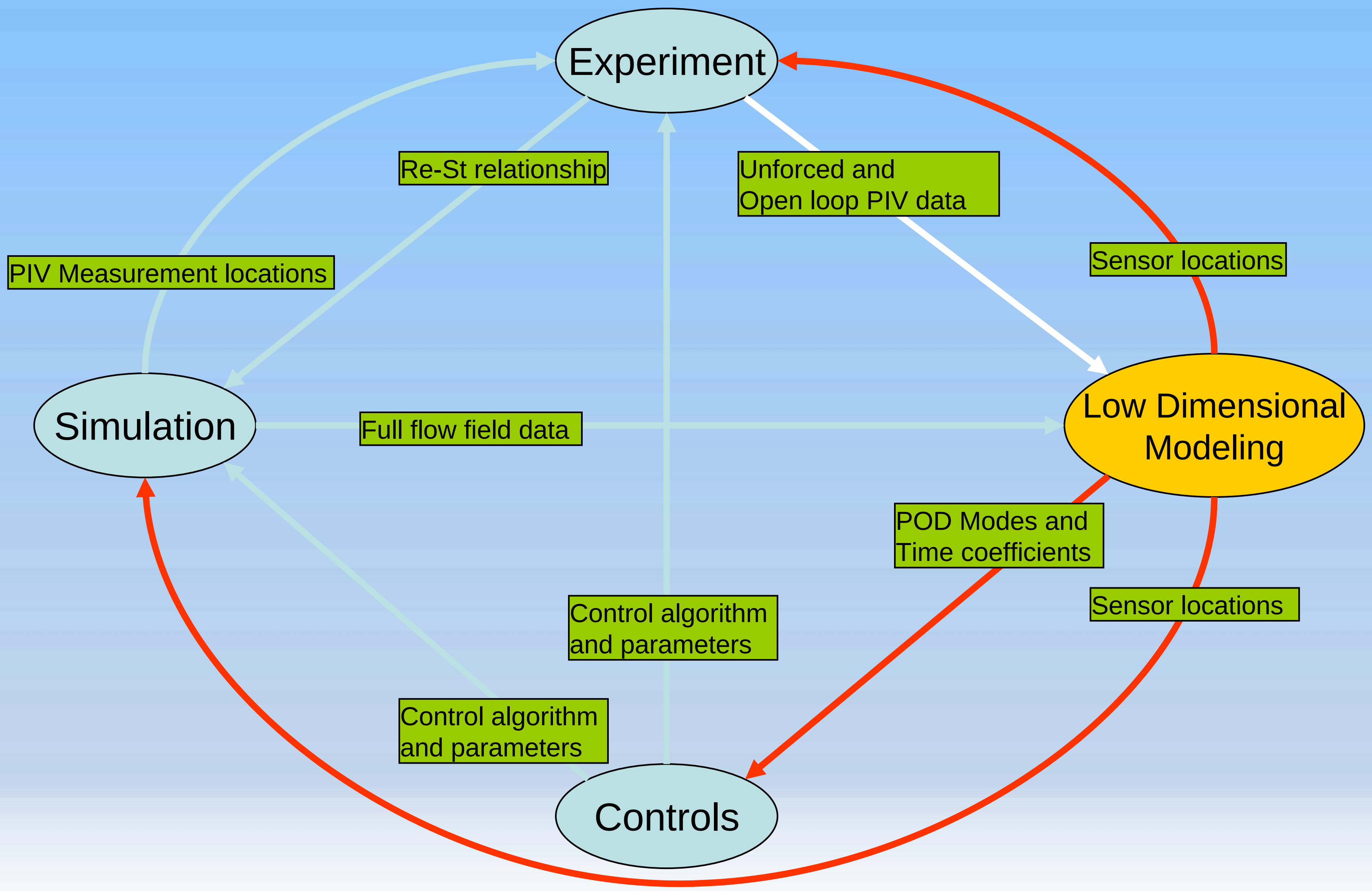


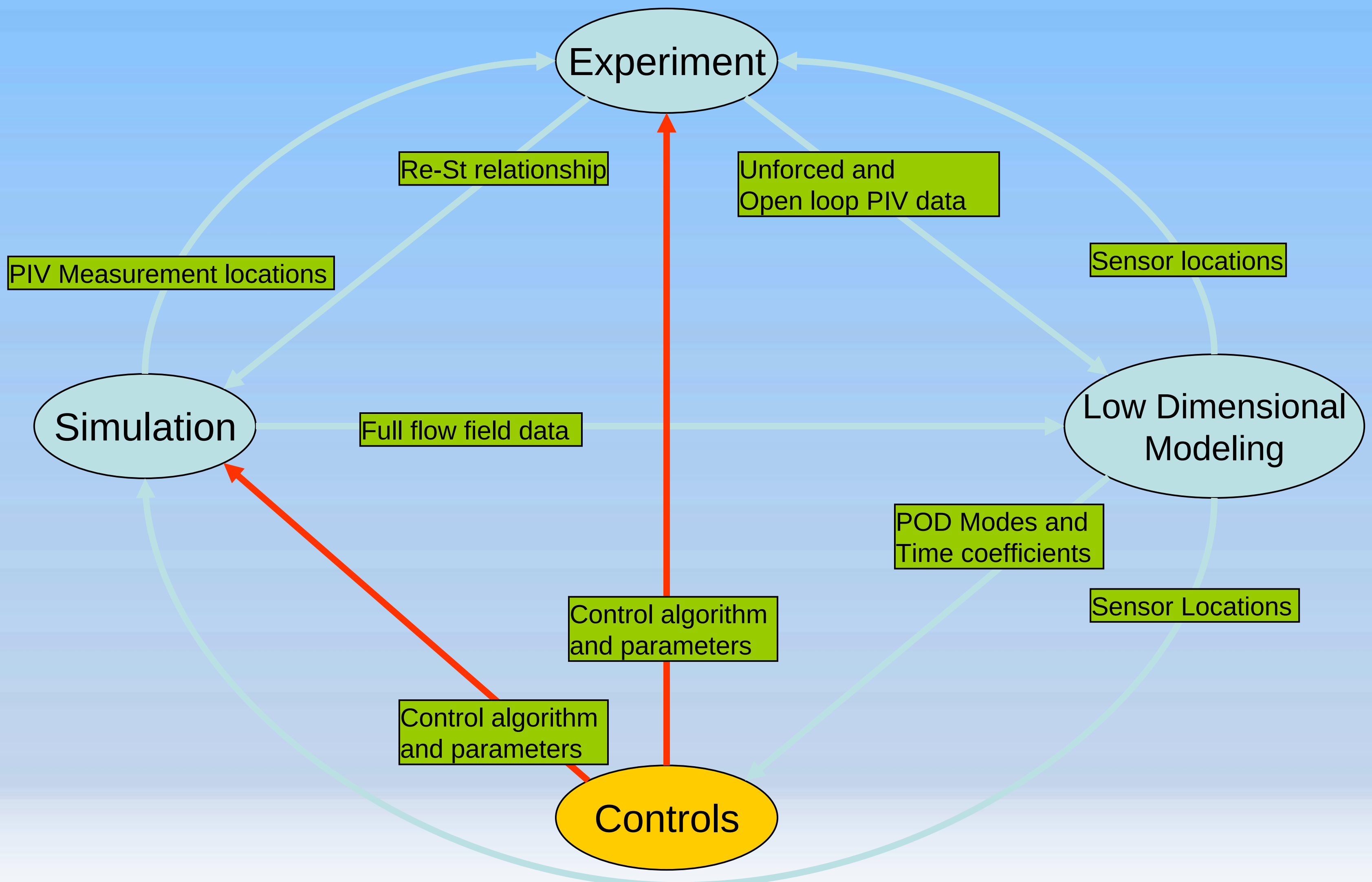
Collaborative Research



Collaborative Research



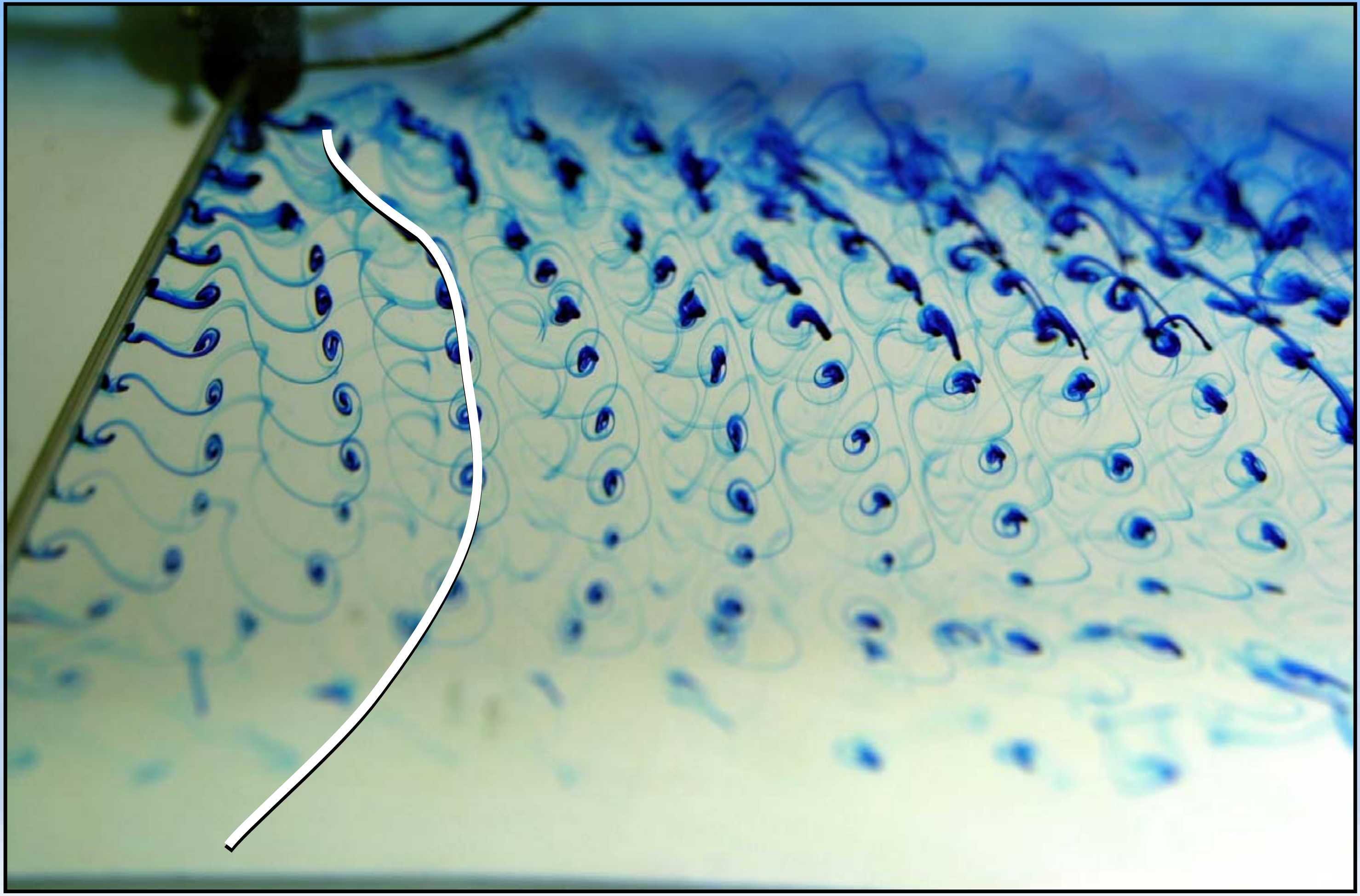
Collaborative Research



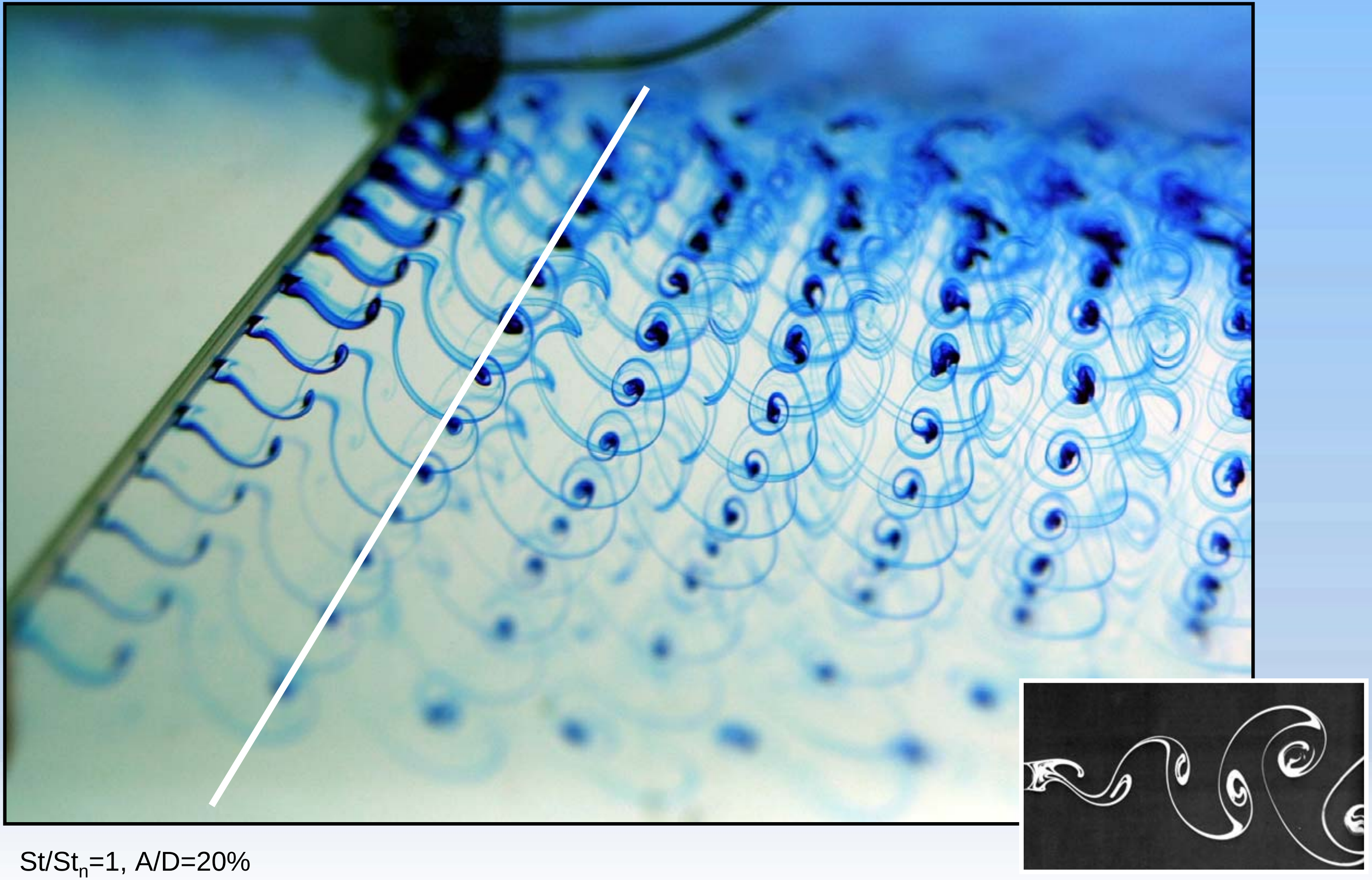
Unforced and Open-loop forced

EXPERIMENTS

Unforced

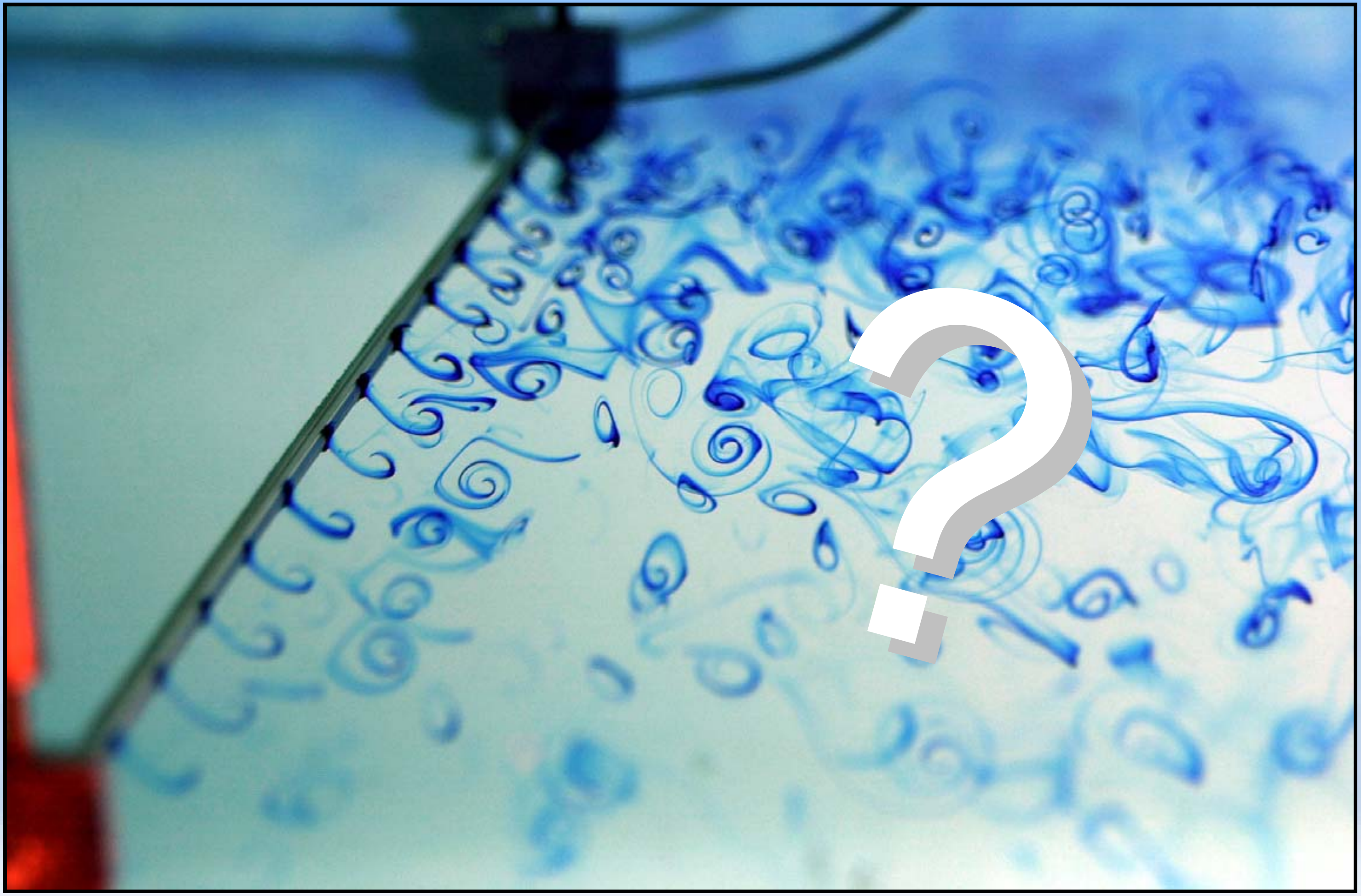


Forced case 1



St/St$_n$=1, A/D=20%

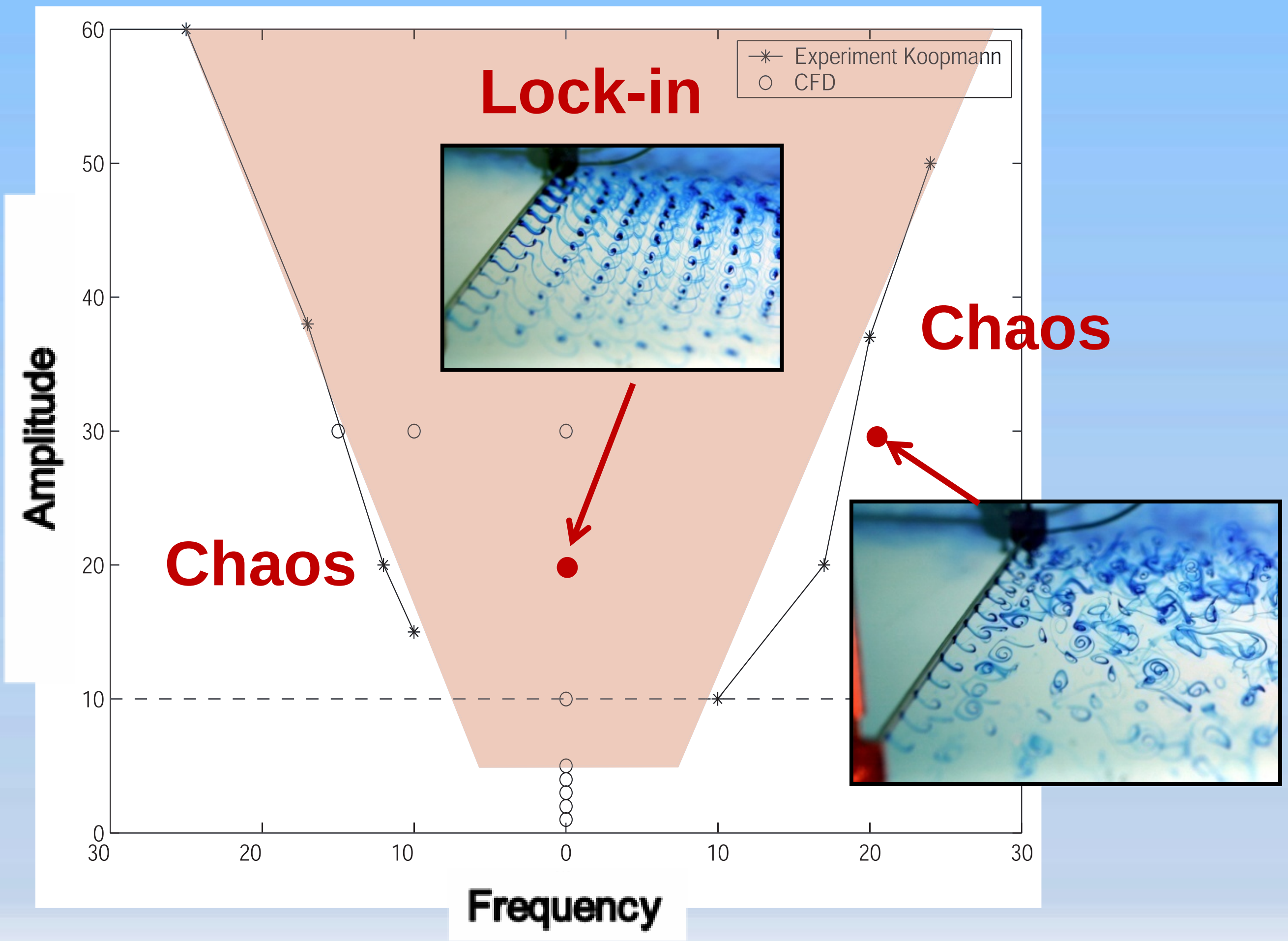
Forced case 2



St/St$_n$=1.26, A/D=30%

Lock-In with Periodic Forcing

- Conventional wisdom: the low-dimensional model should be valid for arbitrary control actions
  - There is a limited envelope of amplitude/frequency of the disturbance wherein the control is effective.



Experiments: Pros and Cons

- Pros
  - Overview/visualization of flow field
  - Easy scan of frequency/amplitude parameter space
  - Final verification
- Cons
  - Expensive model design and building
  - Limited data available
    - Velocity, pressure
    - Field of view
    - State-of-the-art (e.g. PIV) only 2D

Unforced and open-loop forced

SIMULATIONS

Simulations

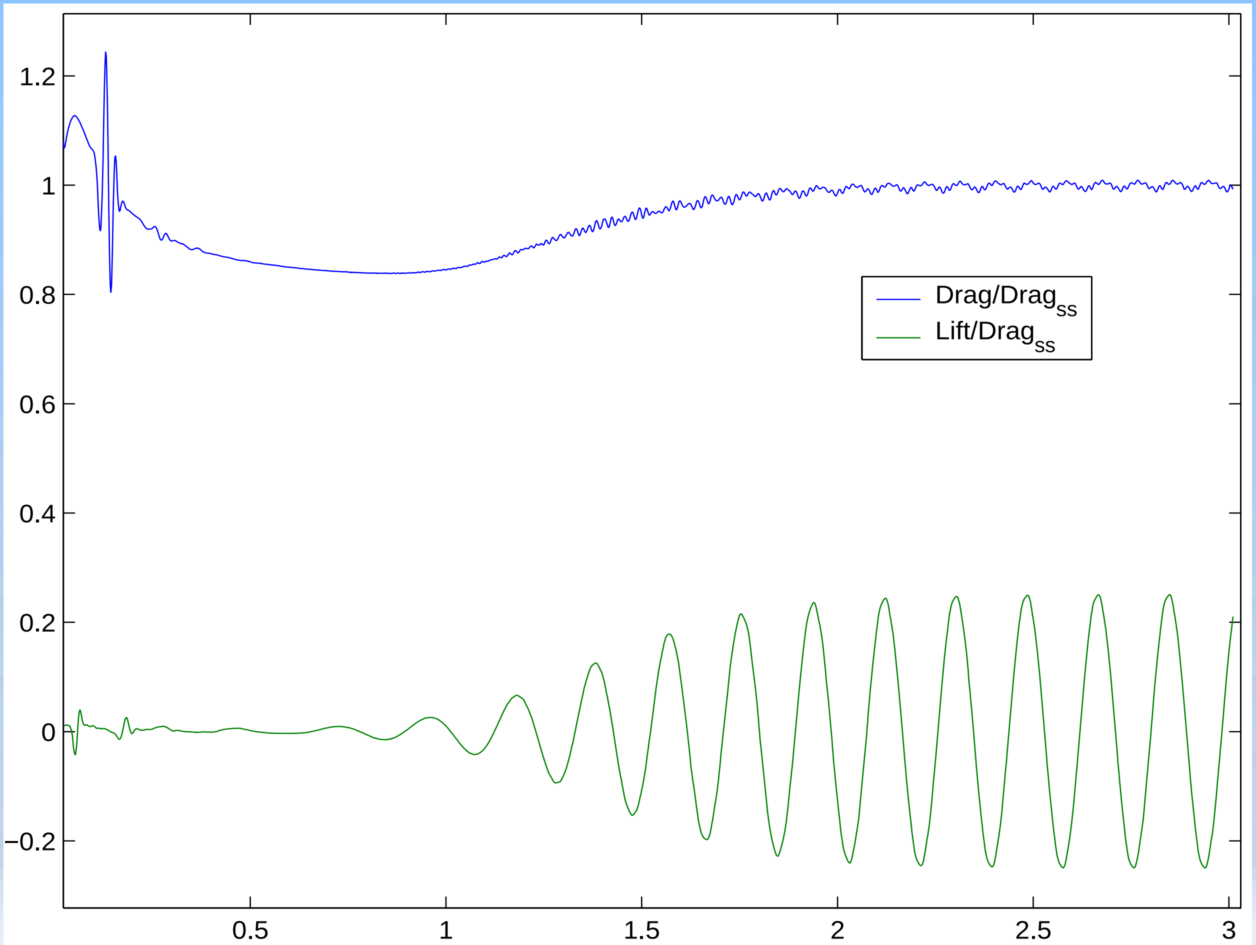
- Cobalt
  - Hybrid-Unstructured, Compressible Solver
  - Point Implicit with Subiteration
  - 2nd-Order Temporal and Spatial Accuracy
  - Turbulence Models
    - RANS: SA, SARC, SST, and others
    - Hybrid RANS/LES: SA-DES, SARC-DES, SST-DES
  - Domain decomposition using ParMETIS (Dr. Karypis, UMN)
  - MPI parallelization
    - Over 98% efficient on 1024 processors
  - Arbitrary Lagrangian Eulerian (ALE) for rigid body motion
  - Variety of motion types: 1DOF, 6DOF

- Matlab
  - Controller development
  - Data analysis
  - Post-processing

- Cobalt-Matlab interface for feedback flow control
  - Developed under current AFOSR STTR Phase I/II
  - HDF5 output

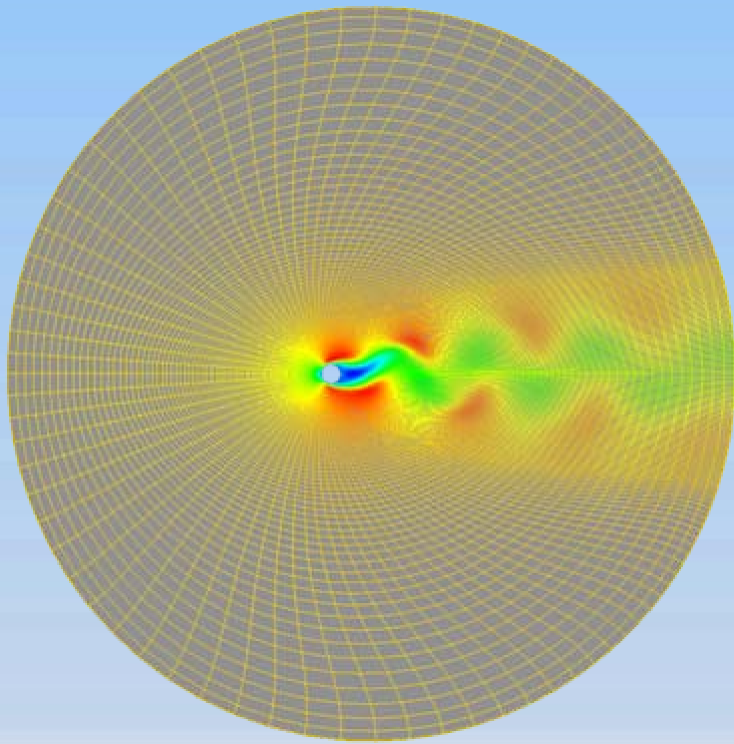
Transient Startup Data Set

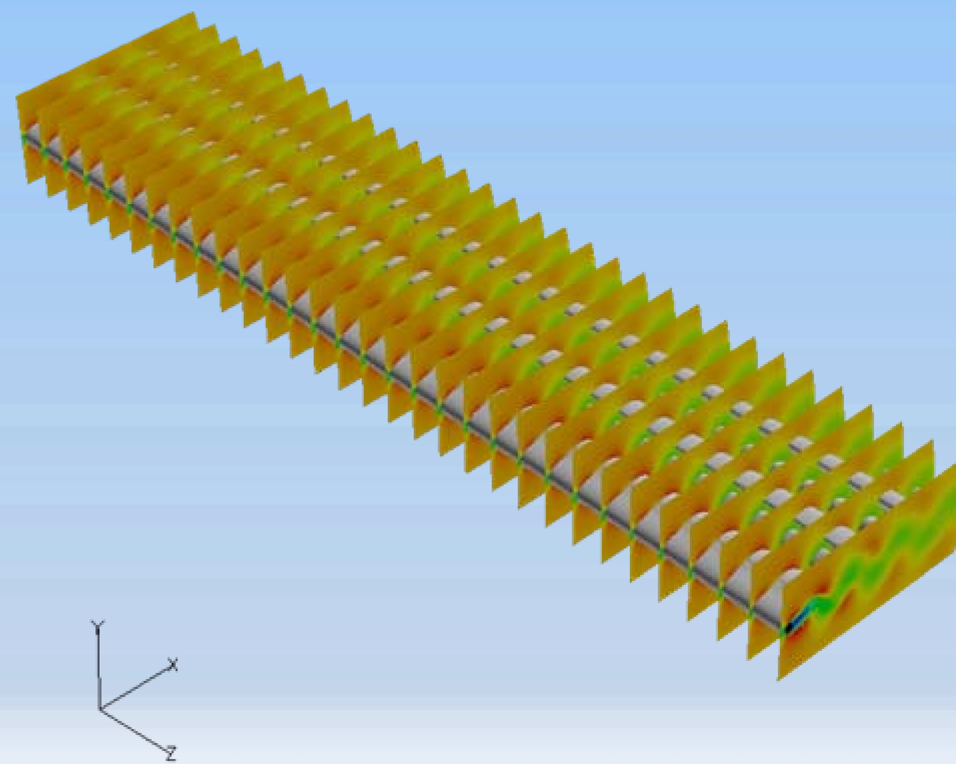
Re = 300



3D cylinder: grid

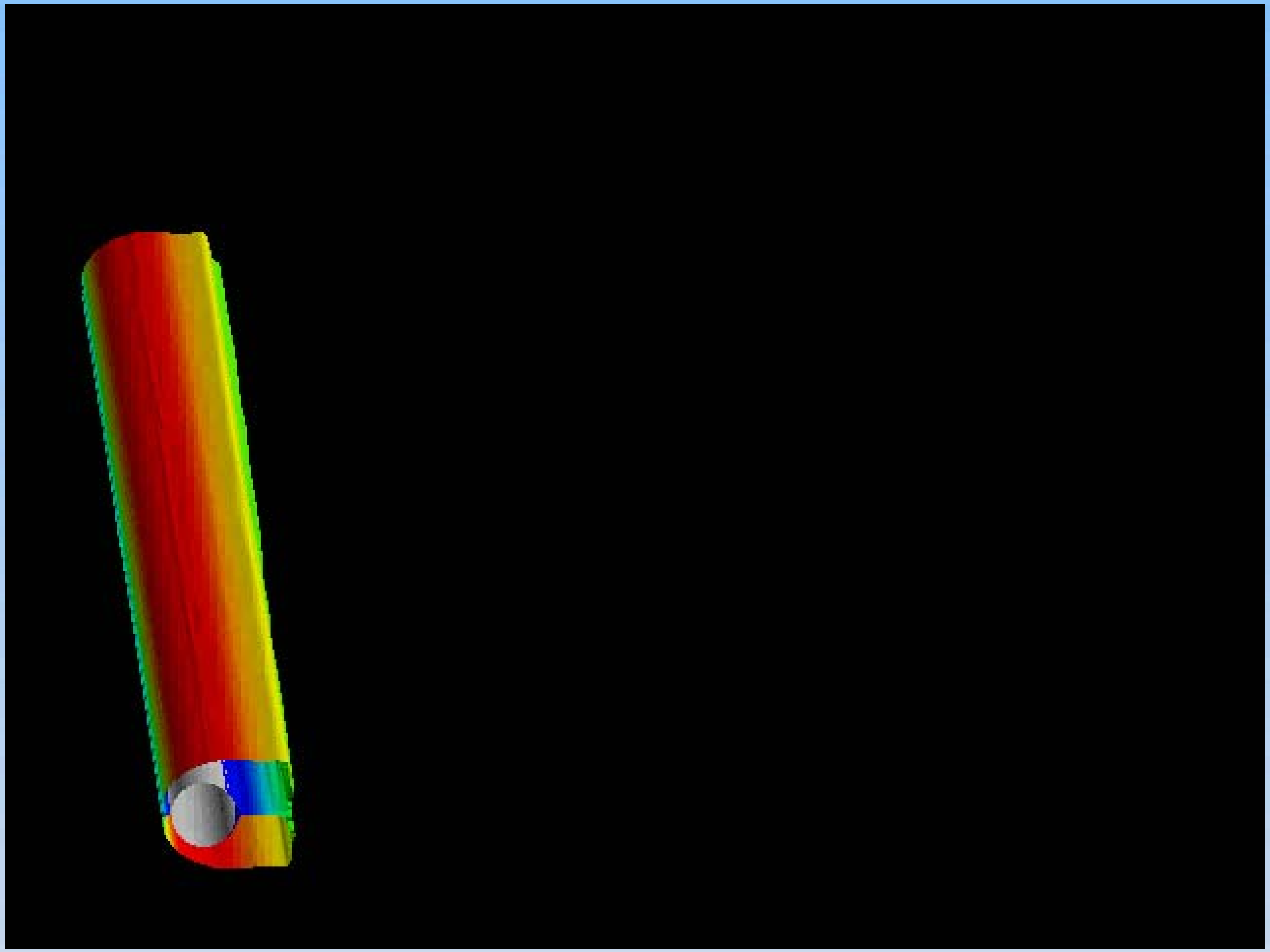
- Body fitted "O" grid extruded along cylinder axis
- 163x198x31 (r, q, z) points





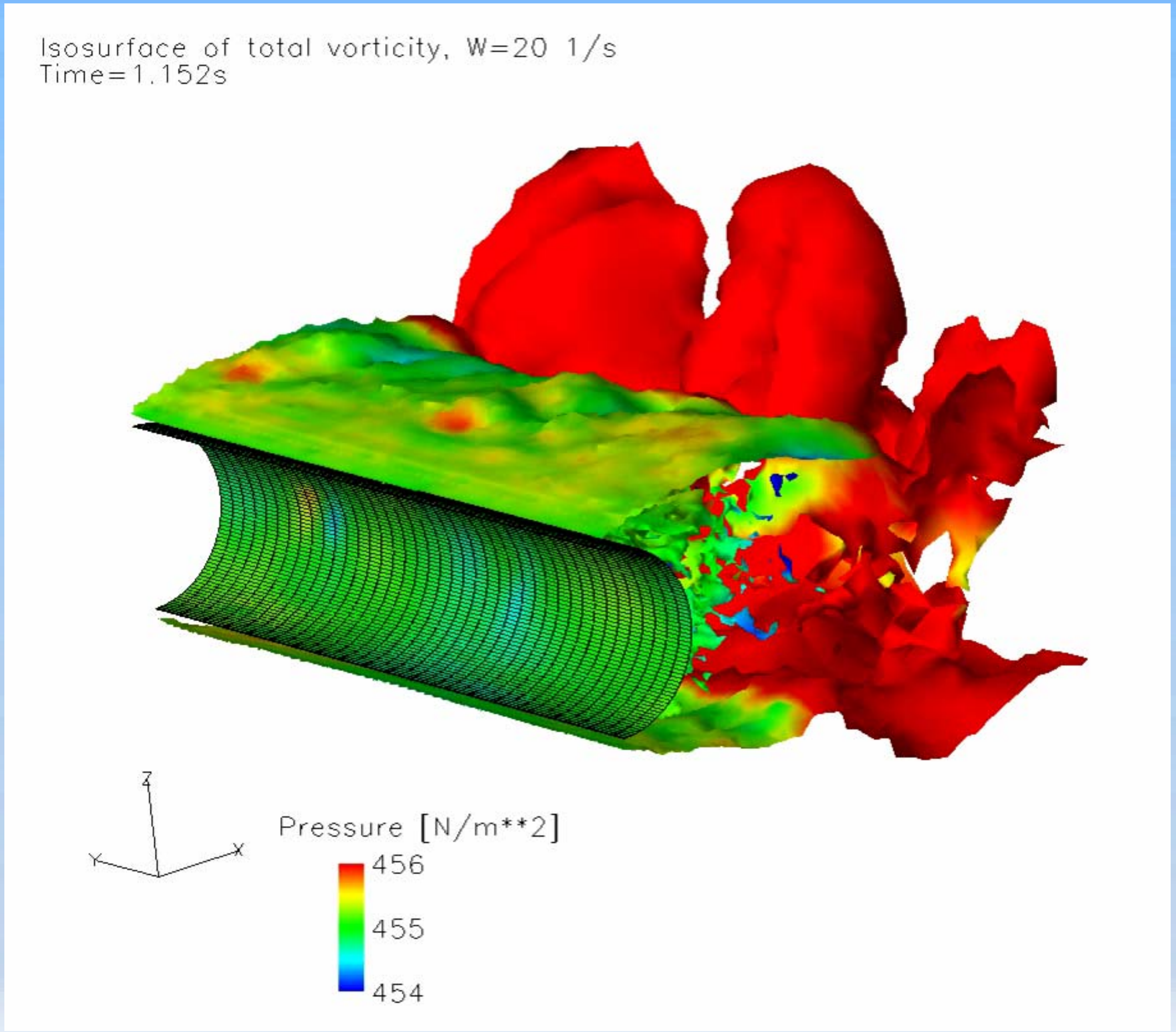
Simulation, Re=100

- L/D=96
- Grid:
  - 2M nodes
  - 31 spanwise planes
- Time:
  - 50 periods
  - 5.6CPUh/period



Simulations, Re=20,000

- L/D=4
- Grid:
  - 1M nodes
  - unstructured
- Time:
  - 180CPUh/period



Simulations: Pros and Cons

- Pros
  - Detailed flow field information
    - Time
    - Space
  - Range of possible flow conditions
    - Reynolds number transients
- Cons
  - Time consuming model/grid design and building
  - Time consuming data generation
  - Limited number of conditions possible
    - Parameter space

MODELING AND CONTROLS

Control of a Ginzburg-Landau cylinder wake model

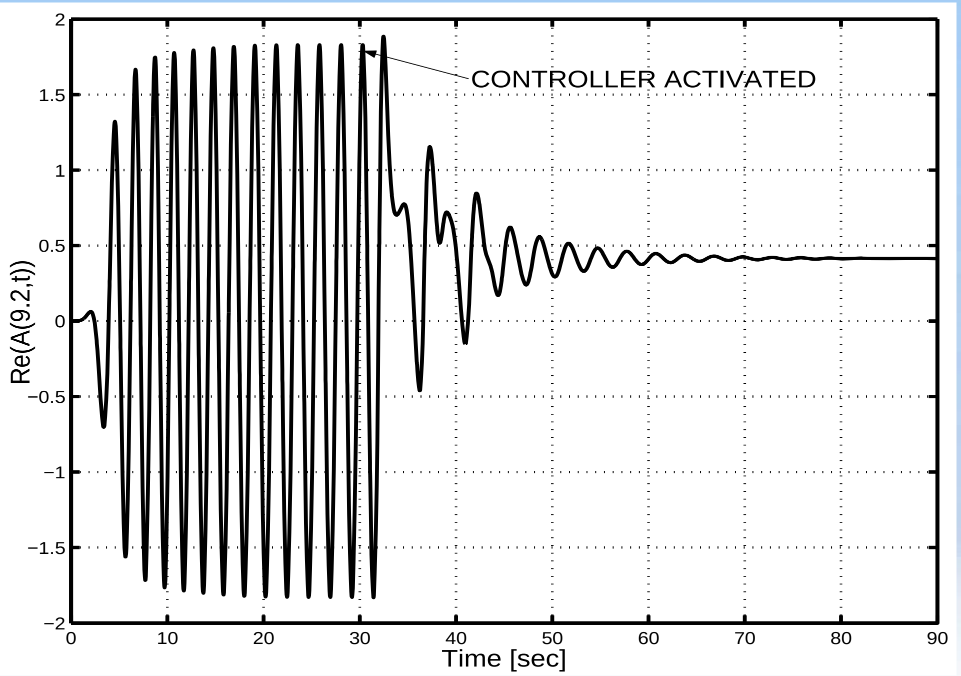
- The complex Ginzburg-Landau (GL) equation model
  - vortex dynamics in bluff-body (such as a circular cylinder) wakes

$$\frac{\partial A}{\partial t} + U\frac{\partial A}{\partial x} = \mu(x)A + (1+jc_d)\frac{\partial^2 A}{\partial x^2} - (1+jc_n)|A|^2 A + F(x,t)$$

- Wake stability of the GL model is defined by the growth parameter $\mu(x) = \mu_o + \mu' x$
  - μ_o is similar to a Reynolds based on the cylinder diameter.
  - For $\mu' < 0$, the stability features similar to 2D cylinder wake.

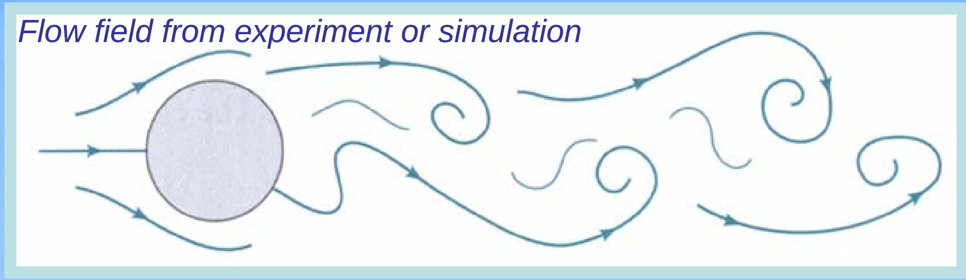
Condition Studied	C_{11}	C_{12}	C_{21}	C_{22}
12.5% Above Critical	1.4524	4.1250	5.1486	4.1643
20.0% Above Critical	4.2744	6.9612	4.7633	0.1911

Look-up table for Coefficients C_{ij} of the modal estimator



Wake Signal at 20% above Critical

Proper Orthogonal Decomposition



N Snapshots of Flow Field
U(x,y,t)
V(x,y,t)

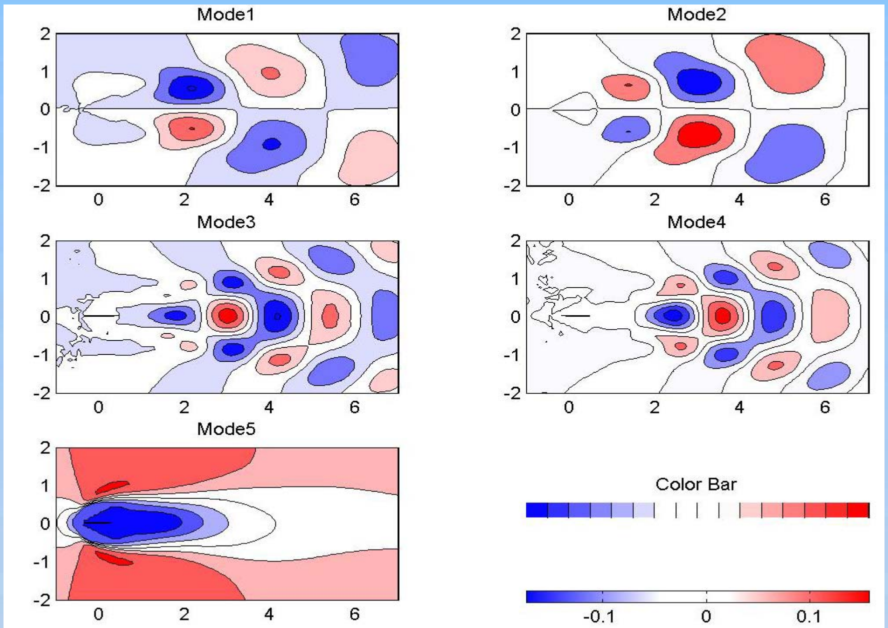
POD
(Proper Orthogonal Decomposition)

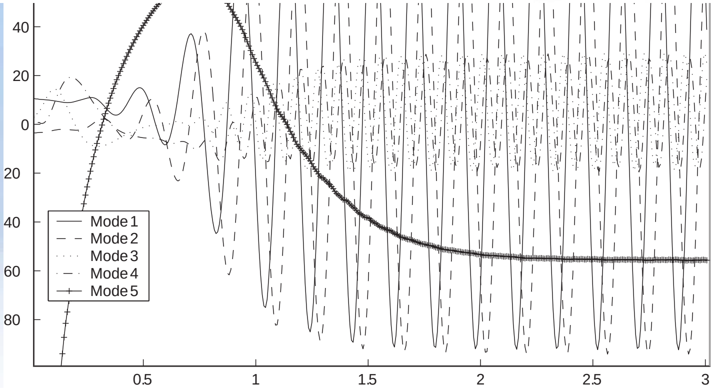
K Temporal Mode Amplitudes
$A_1(t)$
$A_2(t)$
…
$A_K(t)$

K Spatial Modes
$U_1(x,y)$
$V_1(x,y)$
$U_2(x,y)$
....
$V_K(x,y)$

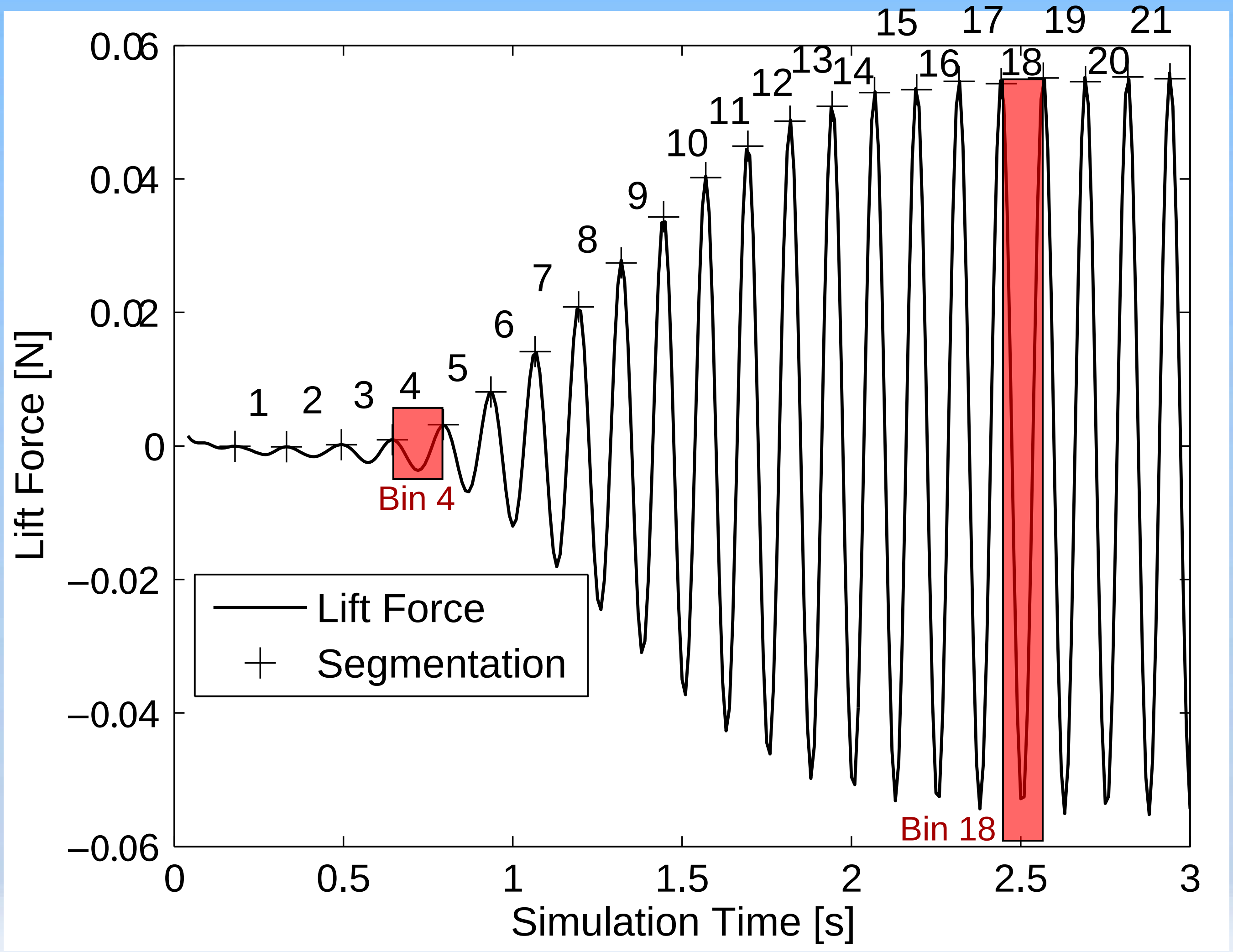
POD and Low Dimensional Modeling

- POD spatial modes
  - Flow characteristics
  - Sensor placement studies
- POD mode amplitudes
  - Low Dimensional Model Development
    - Develop real time nonlinear mapping based on neural networks between measurable quantities (pressure, velocity) and low dimensional states
    - Linear and nonlinear system identification tools
    - Develop control strategies
- Reconstruction of the flow field possible
- Massive reduction of CFD simulation data

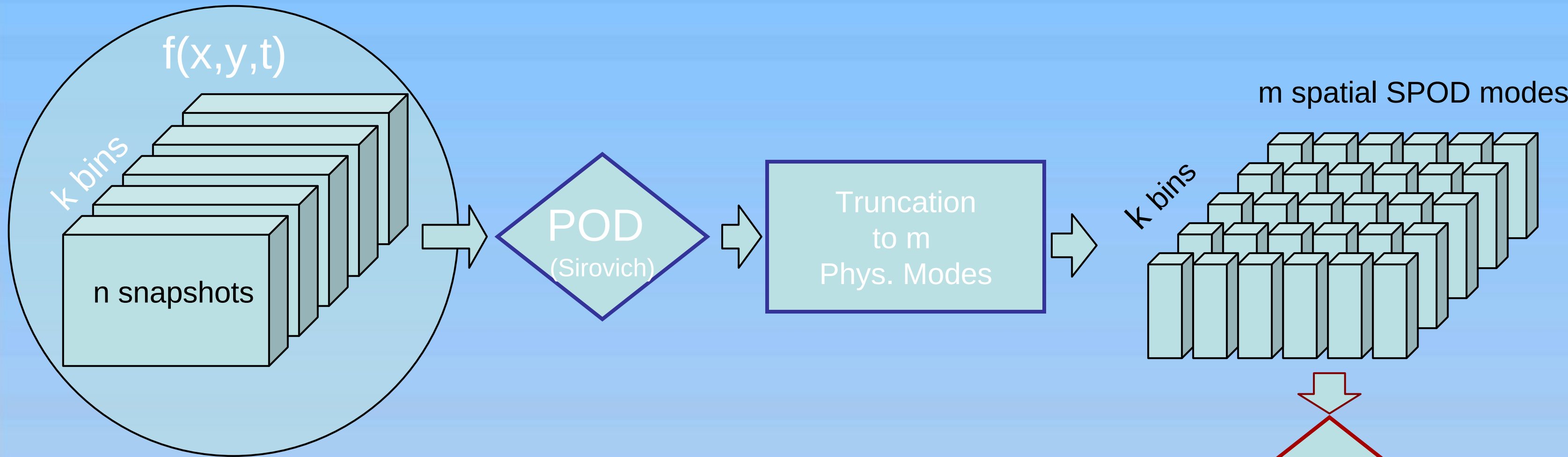


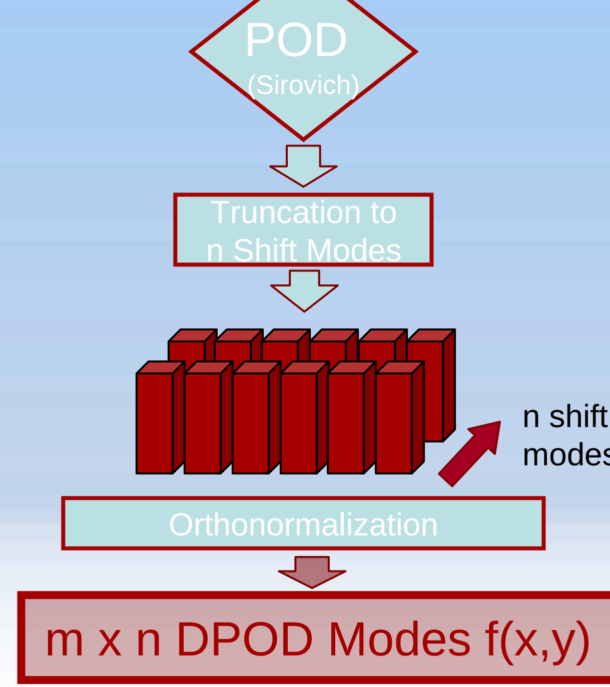


SPOD Segmentation



DPOD Basis Construction





- POD: $$u(x,y,t)=\sum_{j=1}^{J} a_j(t)\varphi_j(x,y)$$
- SPOD: $$u^{(i)}(x,y,t)=\sum_{j=1}^{J} a_j^{(i)}(t)\varphi_j^{(i)}(x,y).$$
- DPOD: $$u^{(i)}(x,y,t)=\sum_{j=1}^{J}\sum_{k=1}^{K} \alpha_{jk}^{(i)}(t)\Phi_{jk}(x,y).$$

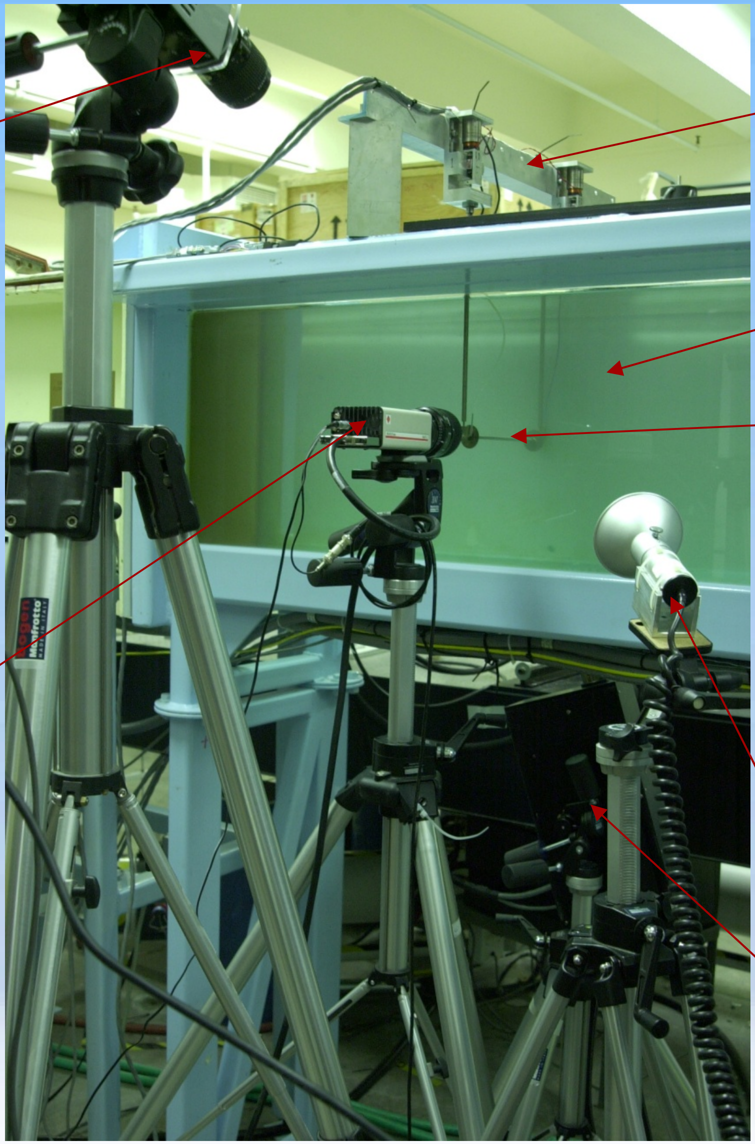
Modeling: Pros and Cons

- Pros
  - Rapid exploration of controller parameter space
  - Implementable in real-time with relative ease
  - Effectively targets the large coherent structures in the flow
- Cons
  - Model building is tough
  - Quality/validity of model depends on underlying data
    - Parameter space

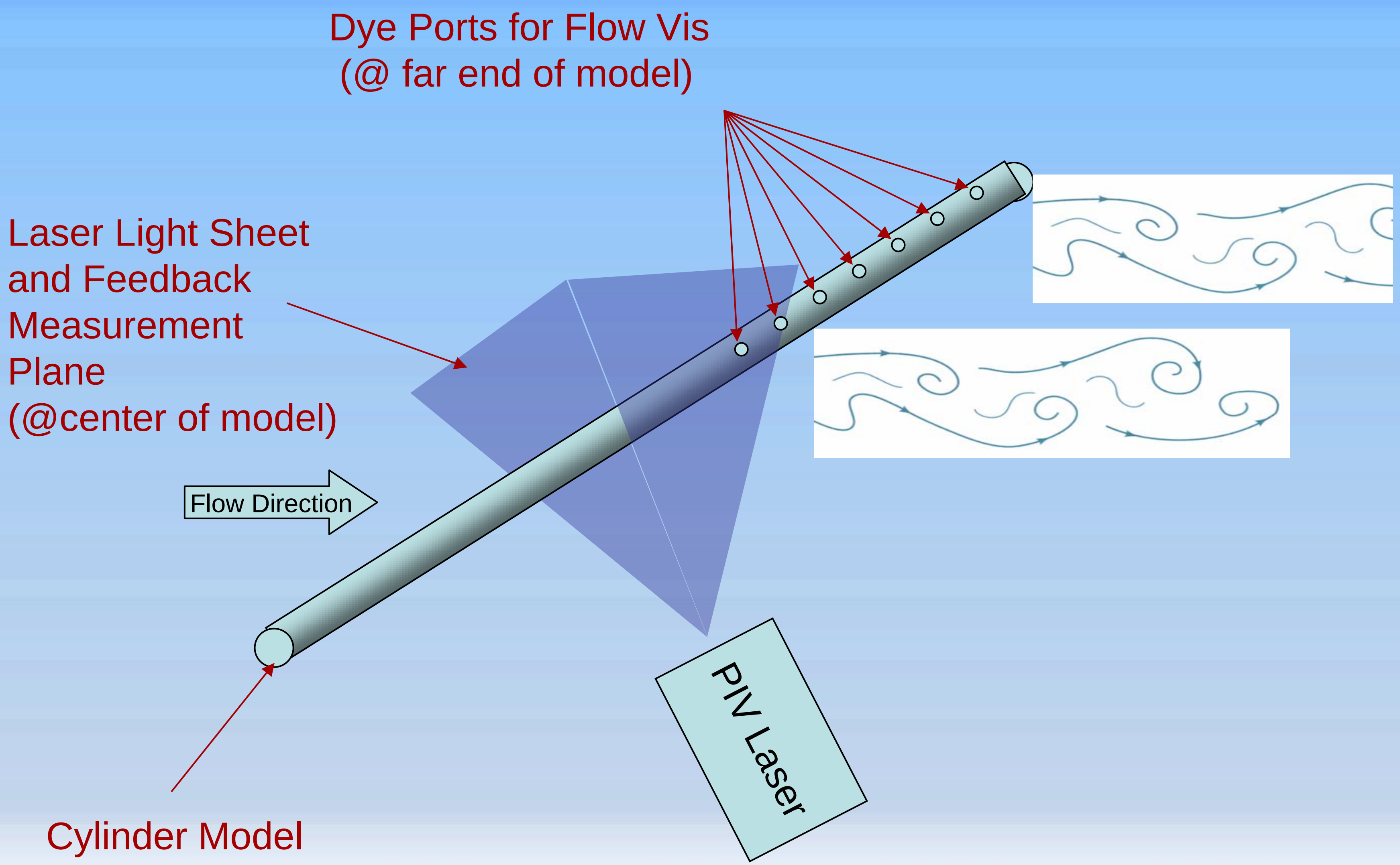
Feedback controlled

EXPERIMENTS

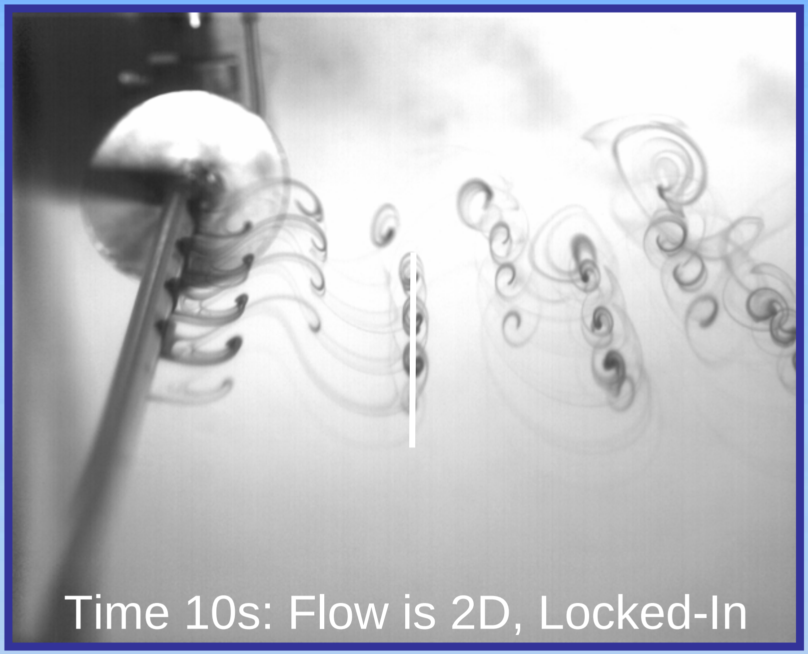
Experimental setup



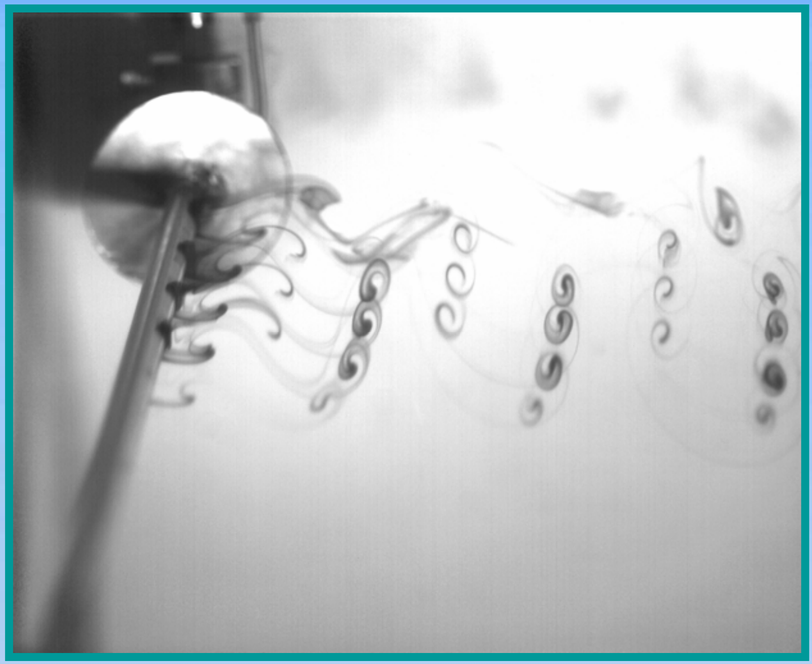
Sensor and Flow Vis Setup

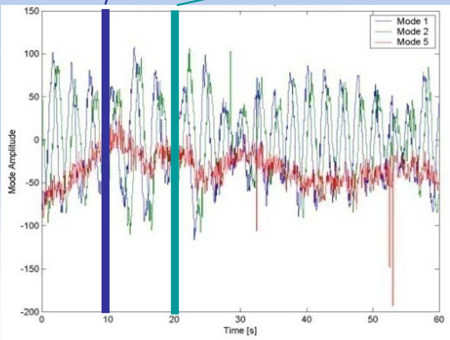


Phase 115° Flow Vis



Time 10s: Flow is 2D, Locked-In

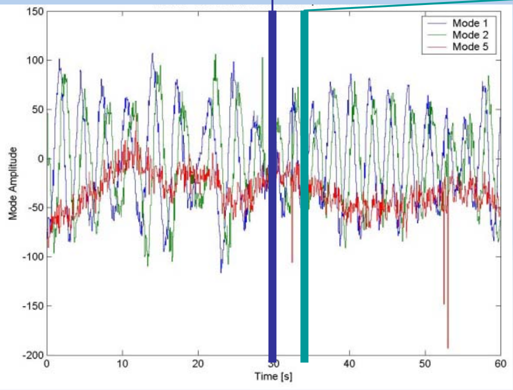




Time 20s: Flow develops spanwise phase variation, vortices shedding delayed in phase at laser light sheet

Phase 115° Flow Vis – Cont'd

Time 30s: Stronger Spanwise phase variation



Time 33.3s: Spanwise phase becomes chaotic, incoherent

Experiments: Pros and Cons

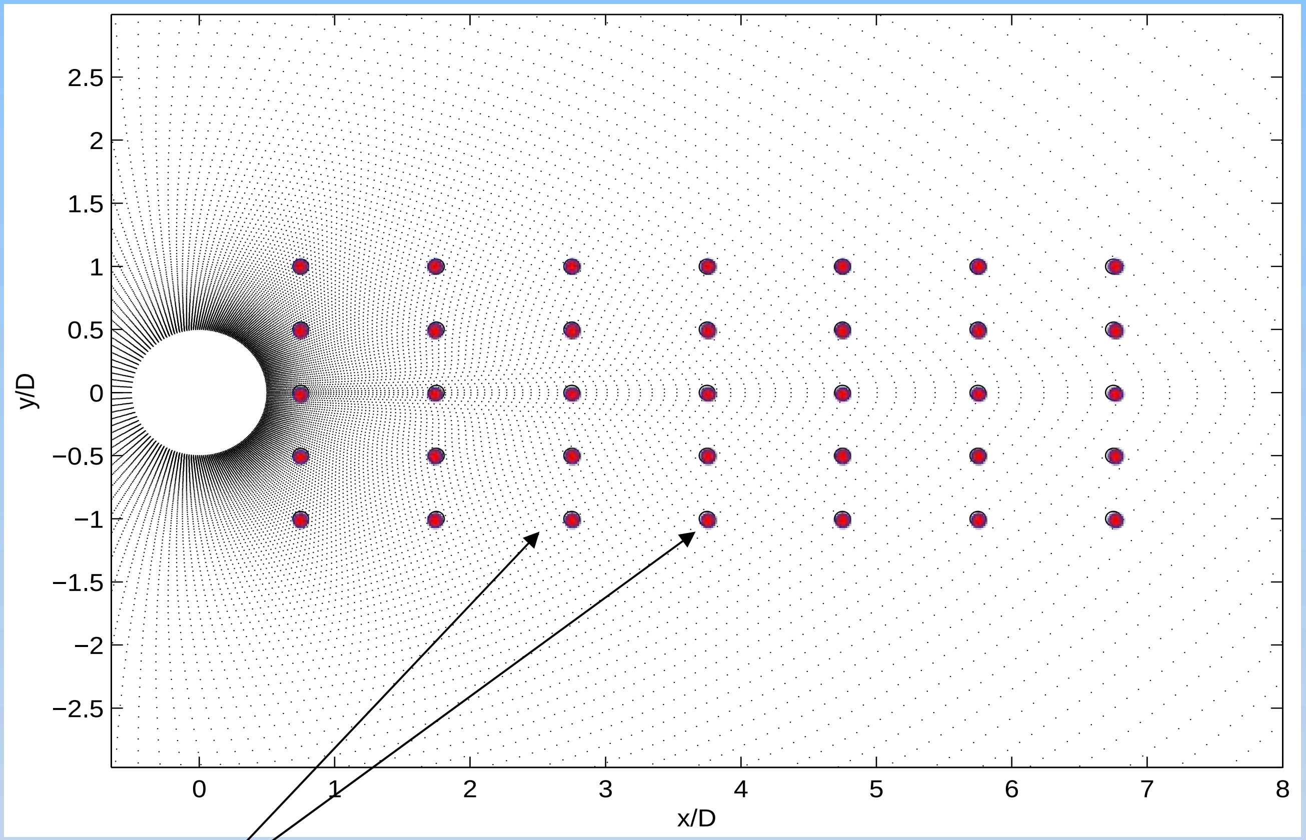
- Pros
  - Verification of entire feedback flow control concept
  - Visualization of flow field
  - Easy scan of controller parameter space

- Cons
  - Expensive feedback control implementation
  - Limited data available
    - Sensors for real time feedback are limited to 2D
      - Wake
      - Surface
    - 3D information only available through flow visualization (offline)
  - Debugging of feedback controller difficult

Feedback flow control

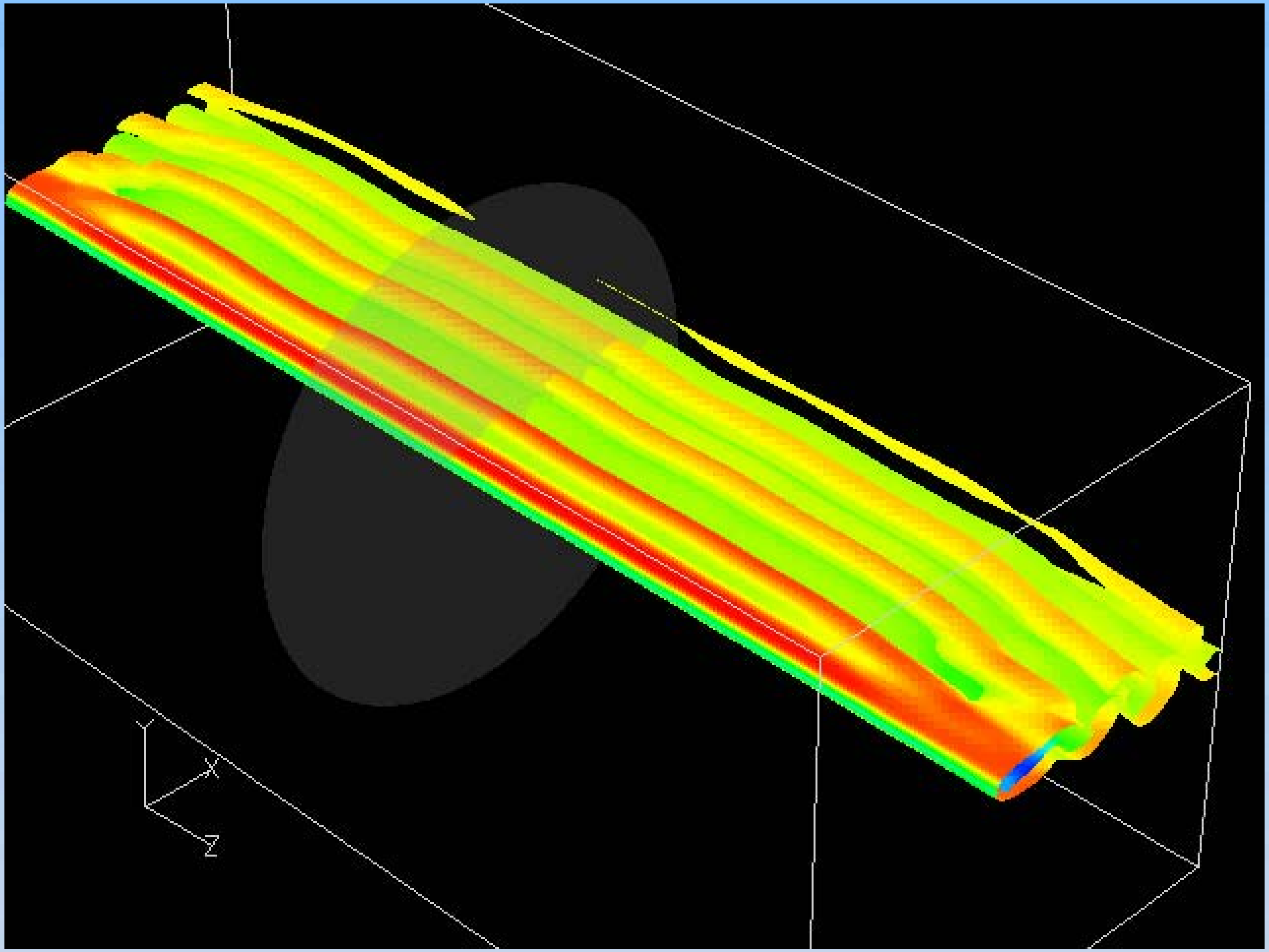
SIMULATIONS

3D cylinder: wake sensors



35 Sensor Locations

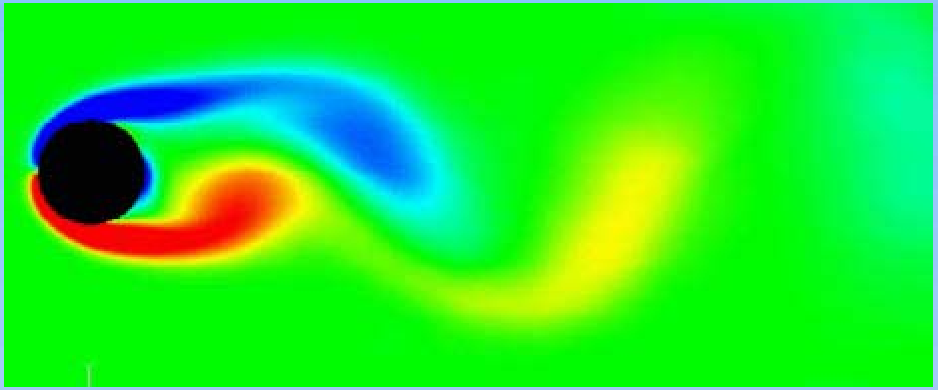
Feedback controlled



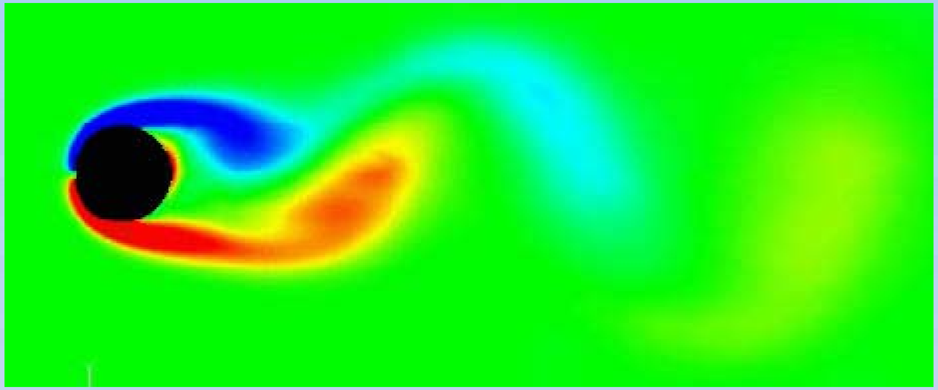
Isocontours of Vorticity colored by U Velocity

Feedback controlled

Centerline



¼ span



Summary

- Develop feedback flow control strategy based on low dimensional model
  - Global flow state estimation using POD
  - State based feedback controller
- Otherwise, this flow is not controllable

Best use for feedback flow control

- Experiments
  - Initial qualitative flow physics understanding
  - Open-loop parameter scans
  - Final testing of controllers
- Computations
  - Detailed data production of key cases (determined by experiments)
  - Debugging of feedback flow control
    - Data availability, no measurement errors
- Modeling
  - Crucial for controller development
  - Initial controller testing
  - Model provides global flow state estimation for real time implementation

Conclusions

- Integration of theory, experiments and simulations
  - more than the sum of all three
  - evaluate best possible use of each at beginning of project
- Need experts in all involved fields
  - But: each expert needs working knowledge of *all* other fields involved
- Communication is paramount
- *State based feedback flow control impossible without IFD*

Outlook

- Application of developed feedback flow control methodology
  - Higher Reynolds numbers
  - Turbulent flows
- New applications
  - Aero Servo Optics
  - Unsteady aerodynamics (MAV, flapping flight)